Novel Phase Imaging by Electron Diffractive Imaging

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Information on electro-magnetic fields in and around nanometer-scaled semiconducting and magnetic devices can be obtained from phase shifts of illumination electron waves. The most established method to observe such phase images is presently electron holography. Another choice could be electron diffractive imaging (EDI), in which complex wave field is reconstructed from a diffraction pattern through iterative numerical calculations under some constraints in real space. In most of papers on EDI reported so far, sample structures has been reconstructed at the atomic level in the field of view (FOV) of several to 30 nm [1, 2]. On the other hand, reconstruction in the FOV of 93 nm has been achieved only when combined to ptychography, in which a lot of diffraction patterns from adjoining nanometer-sized areas are integrated consistently to a reconstruction result [3]. In the present study, we have developed another way to reconstruct a wider FOV up to several hundred nm by EDI.

We used a Schottky-FEG 200kV TEM (JEOL: JEM-2100F) equipped with a post-column energy filter (Gatan: GIF tridium), which has been used for removing inelastic background intensity from samples in the diffraction patterns and also for achieving a camera length large enough for precise sampling of low-angle scattering intensity around the direct spot. Energy-filtered bright field TEM images have been used for the real-space constraints.

When a circular selected-area aperture is inserted at the center of an electron beam, the direct spot is Airy diffraction pattern as shown in Fig. 1(b). By using the image in Fig. 1(a) as the real-space constraint, the phase of the illumination wave in the aperture hole has been reconstructed from Fig. 1(b) as shown in Fig. 1(c). The uniform phase corresponding parallel illumination has been reconstructed successfully in the FOV of 150 nm. Figure 2 shows the reconstruction of a wedge-shaped area of a crushed Si crystal. The energy filter has been used for recording the bright field TEM image in Fig. 2(a) and the direct spot in Fig. 2(b). To avoid dynamical diffraction effects, they have been taken from a direction in which no Bragg spot is excited. The split of the spot has been induced by double refraction at the wedge. The reconstructed phase image in Fig. 2(c) reflects the thickness change of the wedge and agrees well with the thickness map measured by filtered and unfiltered images. Figure 3 shows reconstruction of a p-n junction in GaAs. Although the junction is invisible in the TEM image (Fig. 3(a)), the potential change around the junction influences the direct spot (Fig. 3(b)). In the reconstructed phase image in Fig. 3(c), the junction is clearly seen. The width of the depletion layer and the phase difference across the junction measured in the result agree well with the doping concentration and measurements by electron holography.

So far, we have been succeeded in reconstruction of electron waves in an aperture hole 280 nm in diameter, which is 3 times larger than the FOV achieved by the ptychographic way using a lot of diffraction patterns [3]. Unlike electron holography, the present method doesn't need electron biprisms and vacuum areas adjoining an interesting FOV. We hope that the present method will become an alternative to electron holography in some cases for observations of electro-magnetic fields relating to nanometer-scaled materials [4].

References
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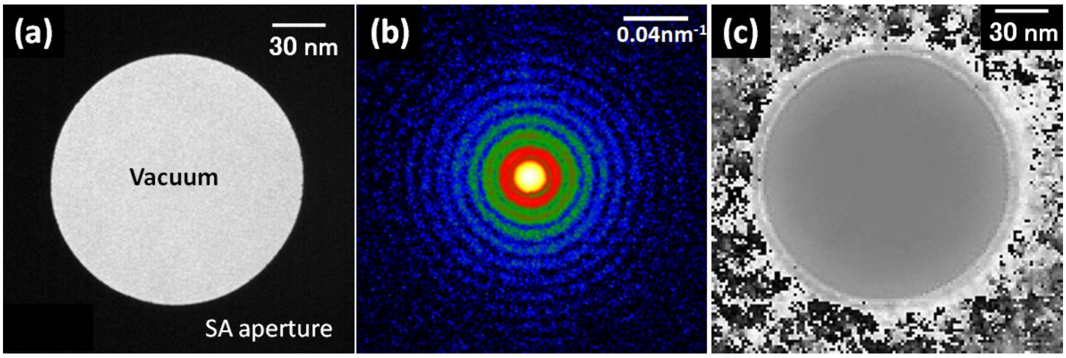

FIG. 1. Phase reconstruction of illumination electron wave by electron diffractive imaging. (a) Bright field TEM image of a selected-area aperture and (b) the corresponding direct spot. (c) Phase reconstructed in the aperture hole.

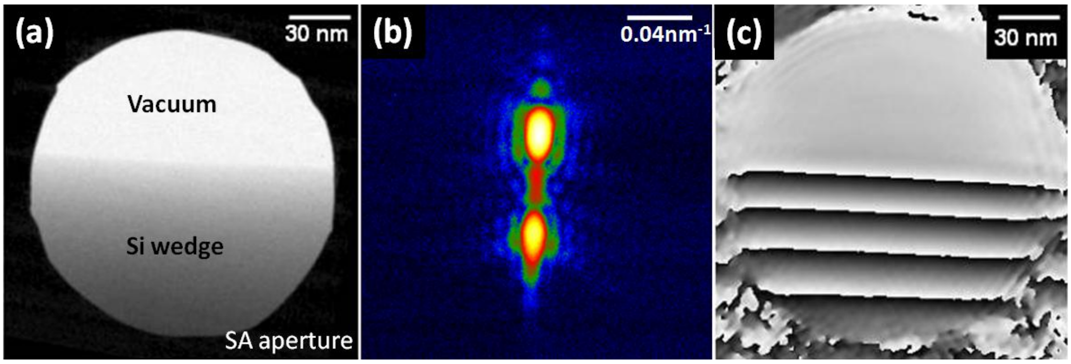

FIG. 2. Reconstruction of the phase image of a wedge-shaped Si crystal.

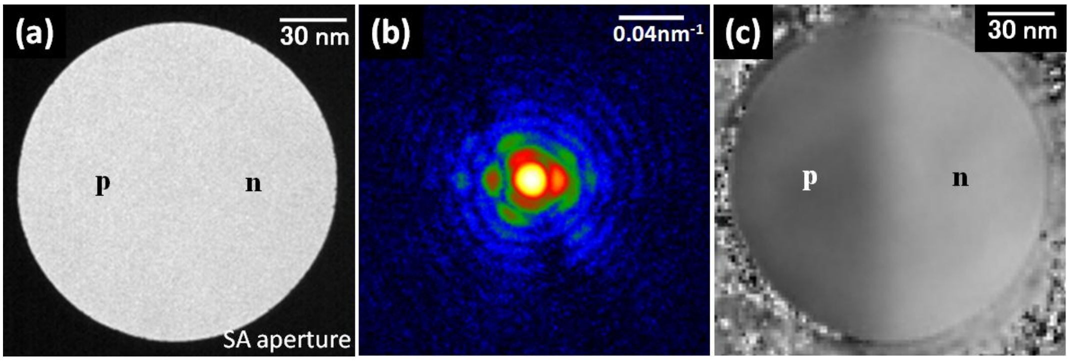

FIG. 3. Reconstruction of the phase image of a p-n junction in GaAs.